

The Snowmass Energy Frontier

Energy Frontier Workshop - Restart

August 30-September 3, 2021

Laura Reina (FSU), Meenakshi Narain (Brown U.), [Alessandro Tricoli \(BNL\)](#)

Welcome (again)
to the Energy Frontier!

Close Captioning



- **Plenary Sessions are captioned by White Coat**
 - Live Transcript available at the StreamText URL
<https://www.streamtext.net/player?event=EnergyFrontier>
 - Captioning also available embedded in zoom (just turn on 'CC')
 - Plenary Speakers: please upload slides a day ahead of talk, if possible

- We thank **Brookhaven National Laboratory (BNL)**

Diversity, Equity & Inclusion (DEI) Office

for the generous support



Diversity, Equity & Inclusion Office

The Diversity, Equity & Inclusion Office supports the Lab mission by facilitating the development of a pipeline of qualified, diverse candidates, ensuring equitable treatment for all employees, and helping to create an environment that encourages respect for individual differences.



Hang-out Rooms and Parallel Sessions in Zoom

- **To step out of main Zoom room and talk with one/more colleagues at a time, while the main meeting continues → Breakout Rooms have been created:**

Hangout room 1, 2, 3

(more can be created if needed, let us know)

Breakout rooms are NOT recorded, NOR captioned

- Make arrangements with colleagues, e.g. with a personal message in Zoom chat
 - Click on *Breakout Rooms* symbol in Zoom
 - Choose one of the three Hangout Rooms, and click ‘*Join*’ where the number of participants is displayed, next to the breakout room name
 - To return to main Zoom room click on ‘*Leave room*’ button
- **Same Zoom link is used for Parallel Sessions as for Plenaries:**
 - **Once you are connected to the main Zoom room, join the Breakout Room corresponding to the session you want to attend**

Energy Frontier Workshop Goals

- **Snowmass reports delayed to 2022 due to ongoing COVID-19 pandemic** ([announcement](#))
- **EF slowed down its activities until end of June, 2021**
 - Community continued to work collaboratively
 - Monte Carlo production activities continued to support the needs of EF
 - Occasional and informal Topical Group ‘conversations’ to assure scientific continuity and support of ongoing activities

- **EF Community Workshop goals:**

- Regroup after the few months of slowdown/pause of Snowmass activities
- Assess progress made so far
- Share new studies that may have been started in the meantime
- Identify gaps in our strategies
- Update the community with schedule, goals and plans for the upcoming months towards the final reports in summer 2022

The Energy Frontier Group (I)

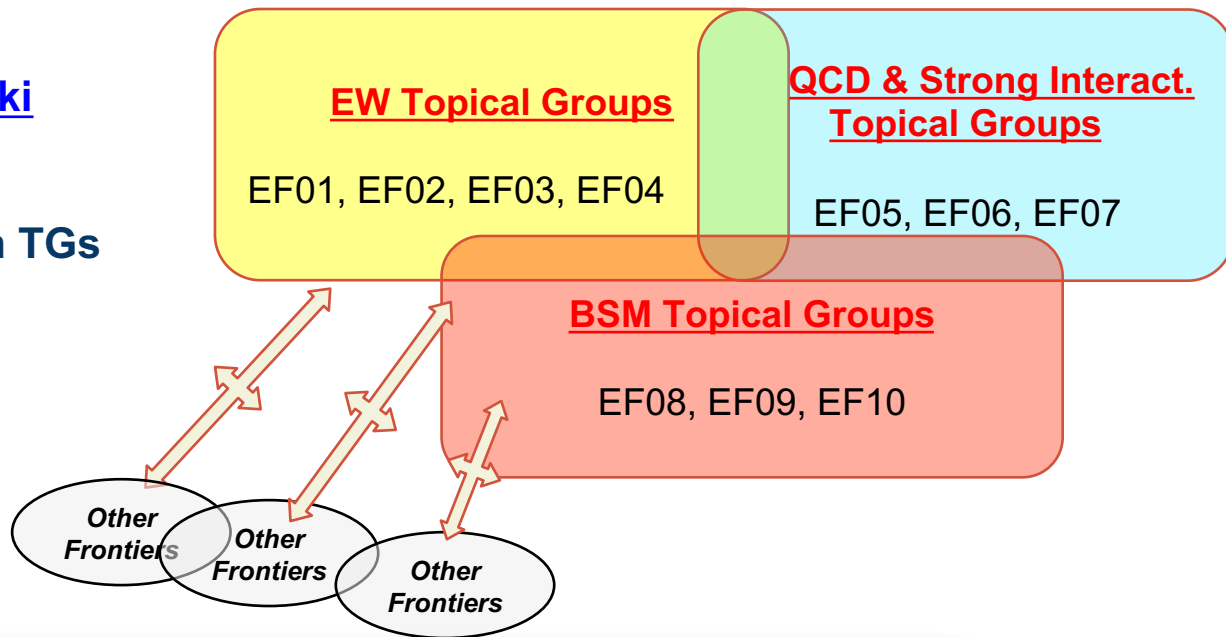
- **EF Convenors:** *Laura Reina* (FSU), *Meenakshi Narain* (Brown U.), *Alessandro Tricoli* (BNL)
- **Ten Topical Groups (TGs):**

Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL), Andrey Korytov (U Florida), Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook), Isobel Ojalvo (Princeton)
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU), Doreen Wackerroth (Buffalo)
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland), Ayres Freitas (Pittsburgh), Junping Tian (Tokyo)
EF05: QCD and strong interactions: Precision QCD	Michael Begel (BNL), Stefan Hoeche (FNAL), Michael Schmitt (Northwestern)
EF06: QCD and strong interactions: Hadronic structure and forward QCD	Huey-Wen Lin (MSU), Pavel Nadolsky (SMU), Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT), Swagato Mukherjee (BNL)
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL), Elliot Lipeles (UPenn), Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin), Zhen Liu (Maryland), Simone Pagan-Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund), LianTao Wang (Chicago)

- **Monte Carlo Task Force and Production Team:** coordinated by **John Stupak** (U. Oklahoma)
 - 1) Assess the MC needs \Rightarrow “Task force” (work completed)
 - 2) Produce MC samples \Rightarrow “Production Team” (ongoing)

Topical Group Activities

- General [Energy Frontier Wiki](#)
- Electroweak TGs
 - EF01, EF02, EF03, EF04
- QCD and Strong Interaction TGs
 - EF05, EF06, EF07
- BSM TGs
 - EF08, EF09, EF10



Multiple Ongoing Activities

- See Topical Group [Wiki pages](#) and [indico meeting agendas](#) for details of ongoing activities
- [EF calendar](#) and [communications](#)

The Energy Frontier Group (II)

- **Liaisons:** high-level and bi-directional communication b/w Frontiers

Other Frontier	Liaisons
Neutrino Physics Frontier	André de Gouvêa (Northwestern)
Rare Processes and Precision	Manuel Franco Sevilla (Maryland)
Cosmic Frontier	Caterina Doglioni (Lund)
Theory Frontier	Laura Reina (FSU)
Accelerator Frontier	Dmitri Denisov (BNL), Meenakshi Narain (Brown)
Computational Frontier	Daniel Elvira (FNAL)
Instrumentation Frontier	Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
Community Engagement Frontier	Daniel Whiteson (UCI), Sergei Gleyzer (Alabama)

- Renew interest in Snowmass community for Muon Collider:
Muon Collider Forum established with *Accelerator and Theory Frontiers* → [Wiki \(new\)](#)

Muon Collider Forum Coordinators

EF: **Kevin Black** (U. Wisconsin-Madison), **Sergo Jindariani** (Fermilab)
AF: **Derun Li** (LBNL), **Diktys Stratakis** (Fermilab)
TF: **Patrick Meade** (Stony Brook U.), **Fabio Maltoni** (Louvain U., Bologna)

The Energy Frontier Group (III)

- **Snowmass thrives on the participation of Early Career (EC) physicists and offers an ideal environment for young people to get involved and promote their own initiatives**

Early Career Representatives

- **Grace Cummings** (U. Virginia) - gec8mf@virginia.edu
- **Matt LeBlanc** (U. Arizona) - matt.leblanc@cern.ch

- EC leadership is for a 3-month term (staggered): Grace and Matt are current EF representatives
- Get in touch especially if you want to get involved in EF activities, but need guidance how to do it effectively: Grace and Matt will help build bridges between projects and new collaborators

Additional Snowmass resources for Early Careers:

- [#snowmass-young](#) and [#welcome-to-snowmass](#) as points of entry for newcomers
- The [Snowmass Early Career](#) twiki, which includes a description of our structure, current leadership, and the SEC calendar of all events.

Our vision for the future of the Energy Frontier

- **The Energy Frontier (EF) group at Snowmass will explore the TeV energy scale and beyond**, under different future accelerator scenarios, including lepton-lepton, hadron-hadron, and lepton-hadron colliders.
- **Sharp physics questions will bring focus to issues pertaining to EF future directions**
 - Focus on “*open questions*”
 - *Re-evaluate existing ideas* and emphasize how existing work can lead to new ideas (for example HL-LHC results may shape future colliders)
 - Identify *new ideas*
 - Highlight *scientific merit of collider options and connections with other Frontiers* to address those questions
- **Snowmass is our time to innovate and set new directions without barriers and constraints set by our collaborations.**

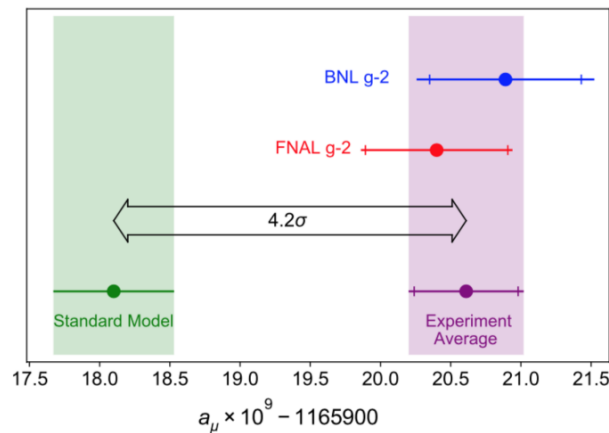
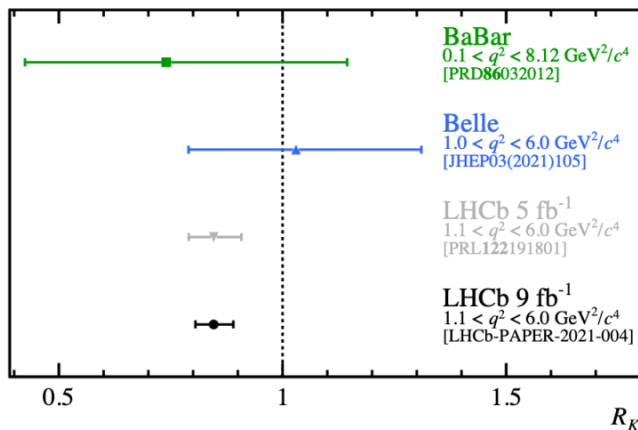
- Energy Frontier Kick-off Meeting on May 21, 2020, [see agenda](#)
- Big Picture questions were discussed in the Panel: “**The importance of the Energy Frontier in the US HEP future planning**” at the “[Energy Frontier Workshop - Open Questions and New Ideas](#)”, July 20-22, 2020 ([Zoom recording of Panel Discussion](#))

A fast changing landscape

- Physics landscape has been changing since we started Snowmass (a year ago)
- Do we have evidence of the breaking of the SM paradigm in the lepton flavor sector?
- How can we probe (directly or indirectly) the underlying flavor structure of the SM ?

...see talk by Wolfgang Altmannshofer this afternoon plenary session

Evidence of Lepton
Flavor Universality
violation at 3.1σ at
LHCb



Data-theory
discrepancy on
g-2 at 4.2σ

Probing the energy scale for new physics

Complementarity with other Frontiers

While slow at the start, the energy frontier is ultimately needed to “win the race”

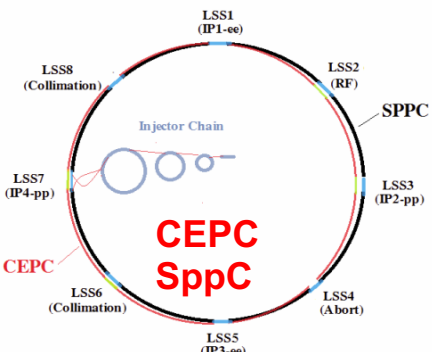


Patrick Meade

Nevertheless if we get indirect hints from existing
or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

- **Collider reach much broader:** colliders needed to test models across the spectrum of all collider observables
- **Unique complementarity** between electroweak precision fits and flavor observables.

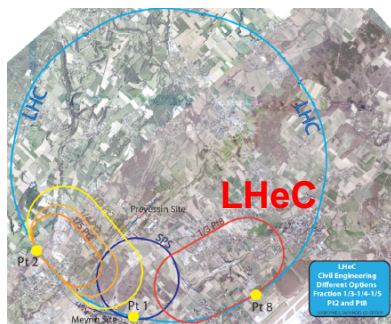


gamma-gamma colliders?

- o large mass reach \Rightarrow exploration?
- o $S/B \sim 10^{-10}$ (w/o trigger)
- o $S/B \sim 0.1$ (w/ trigger)
- o requires multiple detectors
(w/ optimized design)
- o only pdf access to \sqrt{s}
- o \Rightarrow couplings to quarks and gluons

- higher luminosity
- several interaction points
- precise E-beam measurement
(0.1 MeV) via resonant depolarization)
- \sqrt{s} limited by synchrotron radiation

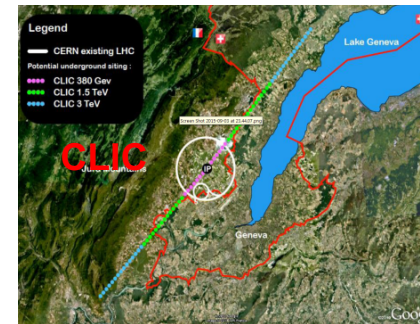
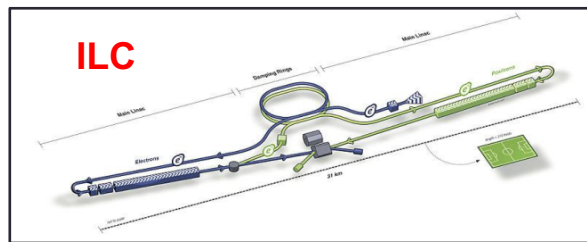
Christophe Grojean



- $S/B \sim 1 \Rightarrow$ measurement?
- polarized beams
(handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- \Rightarrow EW couplings

- easier to upgrade in energy
- easier to polarize beams
- “greener”: less power consumption*
- ▶ large beamstrahlung
- ▶ one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders



Accelerator Benchmark Parameters

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	\sqrt{s}	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV	$\pm 80 / \pm 30$	2
		350 GeV	$\pm 80 / \pm 30$	0.2
		500 GeV	$\pm 80 / \pm 30$	4
		1 TeV	$\pm 80 / \pm 20$	8
CLIC	ee	380 GeV	$\pm 80 / 0$	1
		1.5 TeV	$\pm 80 / 0$	2.5
		3.0 TeV	$\pm 80 / 0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2 M_{\text{top}}$		1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	\sqrt{s}	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)
- FCC pp >150 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- Other emerging ideas:, e.g. $\gamma\gamma$ collider, and the C³ e^+e^- collider [C³=Cool Copper Collider]

Activities and Timeline

- **Broad effort of LOI solicitation through dedicated Topical Group meetings**
 - 376 received - see list [here](#)
 - 268 have EF as primary
 - Cross-frontier LOIs: TF (21), AF (20), IF(17), RF (16), CF (14), NF (11), CompF (9)
- **LOIs have contributed to shaping Topical Group activities**
 - see breakout sessions of the [Community Planning Meeting \(CPM\), Oct 5-8, 2020](#)

❖ If you haven't submitted a LOI, you can still contribute!
just get in touch with your ideas and plans

Timeline going forward

1/21-6/21	6/30/21	7/12/21	8/30/21	9/24/21	3/15/22	5/31/22	6/30/22	7/22	9/30/22	10/31/22
Activity Slowdown	Restart of Activities	DPF Meeting + Snowmass Townhall	Now, EF restart Workshop	Snowmass day	Deadline Contributed Paper Submission	Prelim. TG Reports	Prelim. Frontier Reports	Community Summer Study (UW-Seattle)	Final Reports	Snowmass Book & ArXiv docs

Timeline

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- **Sept. 24, 2021: Snowmass Day**, <https://indico.fnal.gov/event/50538/>
 - Plenary session 12:00-2:00pm (eastern time) with short talks from all frontiers
 - EF parallel session 2:30pm-5:00pm (eastern time) with highlights by topical group
 - Early Career (EC) will be chosen as speakers: they will provide their own perspective and highlight EC studies
- **Winter 2021-2022: few one-day virtual EF workshops by topic (SM, Higgs, BSM, Colliders,...)**
 - Check progress towards March deadline for contributed papers
 - Discuss overlap with other frontiers
- **Spring 2022: EF workshop to review contributed papers**
 - Focus on main themes and messages by contributed papers, towards May deadline for TG reports.
 - Converge on summary plots and other contributions involving multiple TGs or multiple frontiers
- **March-July 2022: circulations of preliminary TG and EF reports, then public readings**

Workshop Agenda

Workshop agenda aims at facilitating discussions on dedicated themes

EST time	Mon	Tue	Wed	Thur	Fri
10 -11 am	Plenary (Organisaion&Plans, EF Highlights, MC production)	Plenary (Theory needs and Progress in Accelerators)	Parallels C (a - EF01+EF02, b - EF05+EF06)	Parallels F (a - EF01+EF03+EF04, b - EF05 and EF06)	Plenary (TG Highlights)
11 -12 pm	Parallels (Global EFT Fits)	Plenary (Emerging Future Collider Projects and Progress in Instrumentation)	Parallels D (a - EF01+EF02, b - EF08+EF09)	Parallel G (a - EF07, b - EF01+EF03+EF04)	Plenary (TG Highlights)
12 -12:30 pm		Break			
12:30 - 1:00pm	Break				
1:00 - 1:30 pm					
1:30 - 2:30 pm	Plenary (Physics Anomalies and Progress in Instrumentation)	Parallels B (a - Session about dark matter summary plots, b - Session with CompF)	Parallels E (a - EF03, b - EF08+EF09)	Parallels H (a - EF03+EF06, b - EF10)	Plenary (TG Highlights)
2:30 - 3 pm	Break	Break			
3 - 4:30 pm	Unstructured Discussions (Discussion with CEF (government outreach and funding)	Unstructured Discussions (Discussion with AF - Muon Collider and new ideas)	Unstructured Discussions (Discussion with AF - e+/e- and hadron colliders, HL-LHC)	Unstructured Discussions (Discussion with AF: advanced acceleration concepts and the collider options)	Unstructured Discussions (Report preparation - result presentation, e.g. plots, tables etc.)

- Emphasis on cross-fertilization across Frontiers
 - Plenary talks (AF, IF, RF)
 - Parallel sessions (CF, CompF)
 - Unstructured discussions (CEF, AF)
- ‘Unstructured discussions’ for brainstorming
 - e.g. how to improve government outreach (Mon)
 - e.g. preparation for Final Reports (Fri)
- TG plans to be outlined in TG reports on Friday’s Plenaries

Summary

- **Ambitious Energy Frontier plans to pave the way towards addressing big questions**
- **Cross-fertilization across fields** (Theory, Cosmics, Accelerators, Instrumentation etc.)
 - Anomalies in related fields require dedicated and long-term effort in the EF to confirm new physics and unveil their origins
- **Energy Frontier activities have taken off in 2020, and restart now at full steam**
 - Great interest and response from national and international community (numerous LOIs, and ongoing contributions)
- ***The 2020 EF organization carries on from 2020, Strategic plans have been laid out, Connection with other frontiers is established, Early Career representation is active, Monte Carlo sample production has started, Studies are on-going***
- **Plenty of time to join activities, propose new studies and address the many open questions**

- Enjoy the EF Workshop !
- Actively participate to discussions and help us make workshop useful

Backup

Big Picture Questions

- Why is physics at the energy frontier important?
- *How should the US be involved in near future and far future energy-frontier machines after HL-LHC?*
- What could be the energy-frontier machines that follow the HL-LHC?
- *How can the US continue to play a leadership role in energy-frontier experiments?*
- *How can the Snowmass process help develop a plan for the energy-frontier research and convince the community about our priorities?*
- *Should we start entertaining the idea of a future collider in the US again? If so, what are our goals, the benefits for the US and the international community, and how can we get there?*
- etc...

- Energy Frontier Kick-off Meeting on May 21, 2020, [see agenda](#)
- These questions were discussed in the Panel: **“The importance of the Energy Frontier in the US HEP future planning”** at the [“Energy Frontier Workshop - Open Questions and New Ideas”, July 20-22, 2020](#)
 - By Jorgen D'Hondt, Nima Arkani-Hamed, Sarah Eno, Vladimir Shiltsev, Xinchou Lou, Young-Kee Kim
 - See [Zoom recording of Panel Discussion](#)

Some “Open Questions” from AF for EF

- Addition of other CoM options for very high energy pp collider? Currently studies use 100 TeV, shall we add an intermediate \sqrt{s} e.g. 70 TeV and lower CoM ?
 - 100 TeV with 16T magnets would have long timeline and high cost.
 - 75 TeV with 12T magnets is feasible but still very expensive.
 - It was suggested to start with 6-7T Nb-Ti magnets. Is 40 TeV CoM of any interest?
- Muon Collider:
 - The \sqrt{s} options presented were multi-TeV (3, 6, 10, 14 TeV)
 - Shall we also pursue muon-collider as a Higgs Factory?
 - Is there interest in \sqrt{s} 30 and 100 TeV “dream” machines – big, very expensive and low(er) lumi
- Gamma-gamma Higgs factory is viable option from AF side [electron beams are used for photons scattering]. Is there a physics interest or a collaboration who is willing to do these studies?
- LHeC: another way to get to Higgs and up to ~ 1 TeV